MEASUREMENT OF BETATRON TUNE ALONG BUNCH TRAIN IN THE KEKB LOW ENERGY RING

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Abstract

The bunch-by-bunch betatron tune along a bunch train has been measured in the KEKB low-energy positron ring. Electron cloud density can be estimated from tune shift under the hypothesis that electrons produced by photo-emission and/or secondary emission are attracted by successive positron bunches and result in shifting the coherent betatron tune of positron bunches. Build-up and decay of the cloud density were measured. The effect of solenoid fields was also measured. The electron density estimated from the tune shift is compared with the threshold density for vertical size enlargement.

1 INTRODUCTION

KEKB[1] is a high intensity multi-bunch collider. The collider consists of two storage rings, the Low Energy Ring (LER) for 3.5 GeV positron beams and the High Energy Ring (HER) for 8 GeV electrons. The target luminosity is $1\times10^{34}\ cm^{-2}\sec^{-1}$, when all rf buckets are filled with harmonic number 5120. However, the achieved luminosity is only around one third of the target value so far. It was observed in single beam mode that the vertical beam size increased above a threshold current for the LER [2]. The increase of the size is caused by a photo-electron instability and is briefly summarized as follows [3,4,5]:

- The threshold of the size blowup is roughly determined by the charge density (bunch current)/(bunch spacing);
- The blowup starts after about 6 bunches from the head of a bunch train, which has typically 60 bunches with 4-rf-bucket (8 ns) spacing [6];
- The blowup is weakened by increasing vertical chromaticity.

Simulation study [7] suggests that the blowup is caused by a single-bunch head-tail instability and the threshold should be determined by the electron-cloud density near the beam. In order to investigate the properties of the electron cloud, a special electrode was installed on a chamber wall [8,9]. Energy distribution of the electrons and their accumulation along bunch trains were measured by giving the electrode a bias voltage. The electron current obtained by those measurements, however, is not electrons that directly act on positron bunches. We have tried to estimate electron cloud density acting on positron bunches by measuring the coherent betatron tunes of individual positron bunches.

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2 GATED TUNE METER

The space charge of the electron cloud makes an electric field which should cause a tune shift in the positron bunches. The vertical tune shift of a positron bunch using a one dimensional model is given by

$$\Delta\nu_y = \frac{r_0\langle\beta_y\rangle L}{\gamma}\cdot\frac{1}{\Delta y}\int_0^{\Delta y}\rho(y')dy', \qquad (1)$$

where r_0 is the classical radius of an electron, $\langle\beta_y\rangle$ the average value of the betatron function, L is the longitudinal length of the cloud along the ring, Δy the vertical displacement, $\rho(y)$ the cloud density and γ the relativistic factor. Assuming a homogeneous density of the electron cloud near a positron bunch, the incoherent tune shift within a bunch would be equal to a coherent one. When the density is not constant, however, tune spread occurs, which may cause a variation of tune spectrum. Thus we can estimate the cloud density from the tune shift and its spectrum.

It is required to measure bunch-by-bunch tune to investigate the photo-electron instability. Recent high-speed electronics has enabled us to detect the bunch-by-bunch signal. Figure 1 shows the betatron tune measurement system using a switch. The tune is measured for a gated bunch with a swept frequency method using a tracking analyzer (Anritsu, MS420K). The output signal of the tracking analyzer is swept in frequency corresponding to a fractional part of the betatron tune and is modulated by a pulse synchronized with the revolution frequency. The amplitude-modulated pulse with width about 50 ns is combined with a feedback signal [10] and both signals are guided to deflector electrodes after amplification. The deflector consists of four stripline electrodes mounted in a chamber. Timing of the deflection pulse is adjusted using a delay module with a step of 2 ns. The bunch signal is picked up by a button electrode installed in a vacuum chamber with a diameter of 64 mm. One bunch is gated from a bunch train in the switch. The amplitude of the gated bunch signal is sampled and detected by a self-triggered pulse. Only the oscillatory part of the gated pulse is detected owing to a feedback gain control formed in a detector circuit. Thus the oscillation amplitude is independent of input bunch intensity. The resolution of the tune measurement is mainly determined by the bandwidth of the tracking analyzer, which is estimated to be ±0.0004 in the present configuration.

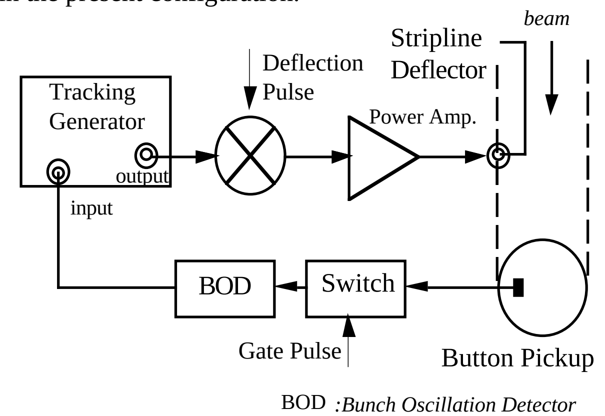

Figure 1: Scheme of gated tune measurement system.

Since the deflection pulse has a width of 50 ns and a rise time of 20 ns, a few forward bunches are also kicked. This perturbation may disturb the electron cloud being measured. In order to investigate this effect, the tune of the gated bunch was monitored while the timing of the deflection pulse was shifted with a constant oscillation amplitude of about 50 μm, less than the rms vertical size, where noise level displayed on the tracking analyzer corresponded to an amplitude of a few μm. It was confirmed that the variation of the measured tune stayed within measurement errors of ±0.0004. Therefore, we found the perturbation of the forward bunches had a negligible effect. An effect of excitation amplitude was also investigated. When the excitation amplitude was increased over a range of more than 20 dB, the change of the tune was found to be within measurement error. Though the result suggests that a nonlinear effect for the excitation is small, the tune measurement was performed with an excitation amplitude of less than the rms beam size so as not to disturb the cloud.

3 MEASUREMENT OF TUNE SHIFT

The bunch-by-bunch tune was measured without collision along a bunch train which has 60 bunches with 4-bucket spacing, where each bunch had almost the same intensity. Three peaks in the vertical tune spectrum of the leading bunch were observed on the tracking scope. The central peak corresponded a pure betatron frequency represented by the m=0 dipole mode. The two sideband peaks indicated betatron oscillation modulated by synchrotron motion represented by the m=1 and m=-1 modes. As the measurement proceeded to rearward bunches, those three peaks were similarly shifted towards a higher tune, while the peaks widened. Figure 2 shows the tune shift as a function of bunch number from the leading bunch, where the original tune is defined by that of the leading bunch in this measurement. Because there are many empty buckets before the leading bunch, its tune is expected to be the same as that of a single bunch. The tune shift linearly increases up to the 10th bunch and tends to saturate behind it. The measured tune shift is caused by a focusing force for all modes, which suggests an interaction between a positron bunch and electron cloud. The behavior of the tune shift agrees with the cloud density obtained by simulation [7].

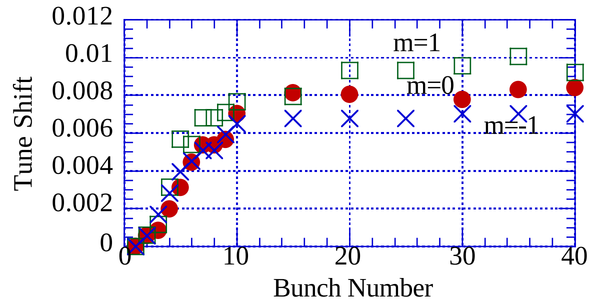

Figure 2: Betatron tune shift along bunch train for three modes of betatron oscillation, where the bunch current is $I_b = 0.21$ mA and the synchrotron tune $\nu_s = 0.015$. The measurement was performed in July 2000 without magnetic fields to trap photo-electrons.

In order to investigate the properties of the electron cloud, an additional bunch was injected behind a bunch train. The tune of the additional bunch was measured as its longitudinal position was shifted, while the train was kept constant. We find the tune shift exponentially decays with a decay constant of 14 buckets or 28 ns as shown in Fig. 3. Though the measurement was performed with the C-yoke magnets described later, the measured decay constant agrees with the simulation [7] using a field free condition.

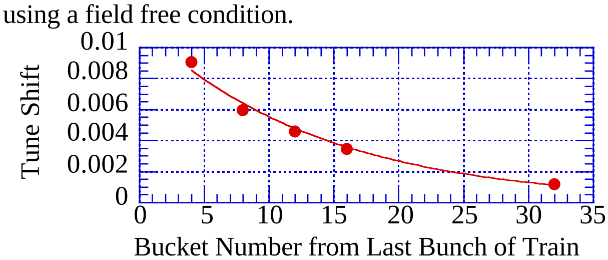

Figure 3: Variation of the vertical tune of an additional bunch as a function of the distance from the last bunch of a bunch train which contains 32 bunches with 4-bucket spacing. The bunch currents are all 0.8 mA.

4 DISCUSSION

The simulation results predict that the threshold for the photo-electron instability is $\rho_{th} = 5 \sim 10 \times 10^{11}$ m^{-3}, when chromaticity is zero and synchrotron tune $\nu_s = 0.015$ [7]. Assuming a constant cloud density near the beam, the tune shift becomes $\Delta\nu_y = 0.004$ to 0.009 at the threshold, using $\langle \beta_y \rangle = 10.9m$ and $L = 2000m$. On the other hand, the measured tune shift varies along the train as shown in Fig. 2 and is also changed by the bunch current and by the bunch spacing. Figure 4 shows the tune shift between the 1st and 6th bunches of a train plotted for various charge densities. The 6th bunch was selected as the threshold bunch for the blowup [6]. The tune shift almost linearly increases with the charge density. It was observed that the vertical size enlargement took place above a charge density of 0.08 mA/bucket using an interferometer [11]. The threshold for the instability is estimated to be around $\Delta\nu_y$=0.0045 from the tune shift measurement, assuming a constant cloud density. Though an extremely simplified condition is used, the measured tune shift is roughly consistent with the predicted value from the simulation.

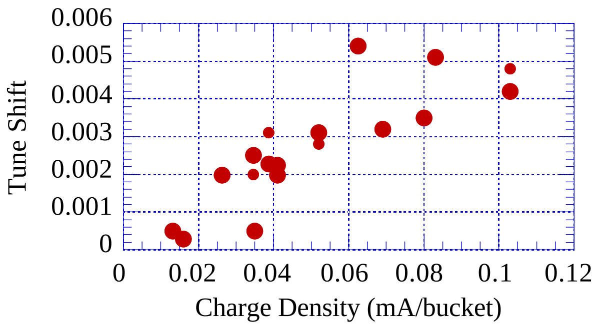

Figure 4: The tune shift of 6th bunch in a train as a function of the charge density, where $\nu_s = 0.011$.

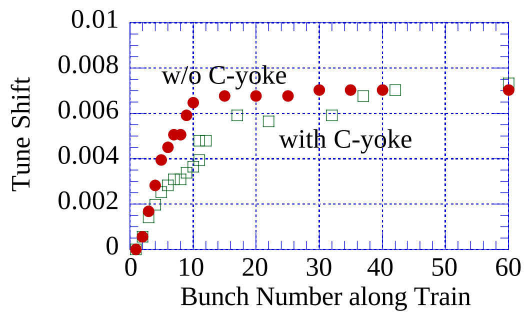

Figure 5: Tune shift along bunch train, with and without C-yoke permanent magnets, measured with $I_b = 0.21mA$ and 4-bucket spacing.

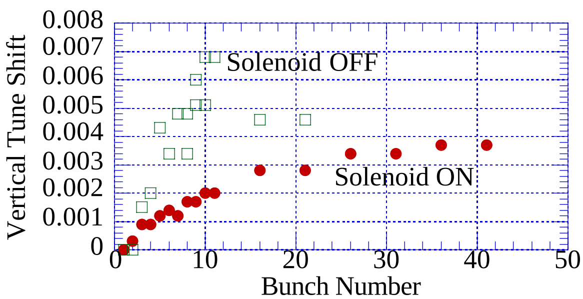

Figure 6: Tune shift along bunch train, with and without solenoid fields, measured with $I_b = 0.25mA$ and 4-bucket spacing.

Intensive efforts have continued to suppress vertical blowup since the early stages of the commissioning. First, permanent magnets attached to C-shaped iron yokes were placed on the chamber surface in the arc sections. The longitudinal length covered by the C-yokes was about 750 m, where the total length of the arcs is 2200 m. The tune shift along a bunch train was compared with and without the C-yoke magnets. A small difference in the tune shift is observed in only the leading part of a bunch train as shown in Fig. 5. On the other hand, the size measurement showed that great improvement was not observed for the threshold, though onset and growth of blowup were somewhat retarded in the bunch train [6]. Second, solenoid fields were applied in the arc sections of the LER after all the permanents magnets were removed. The maximum longitudinal field is 45 gauss and the total length is about 800 m. The tune shift was measured and compared with and without solenoid fields as shown in Fig. 6. A clear difference of the tune shift was observed in the leading part of a train. Remarkable improvement for the threshold was observed in the size measurement [4]. However, we can see that the tune gradually increases along a train, even when the solenoids are fully excited. Table 1 shows linearized tune shifts per bunch in the leading part of a train for each configuration. Comparing between the C-yokes and the solenoid, the solenoid is more effective than the C-yokes.

Table 1: Linear tune shift per bunch along a train.

condition	tune shift $\times 10^{-4}$
Non-correction	9.0 ± 1.0
C-yoke	5.5 ± 0.5
Solenoid	2.8 ± 0.5

5 SUMMARY

A fast gate module enables us to measure bunch-by-bunch betatron tune in multi-bunch machine such as KEKB. The tune shift measurement is useful to estimate the variation of electron cloud density along a train of positron bunches. The measured build-up and decay times of the cloud are consistent with the simulation. It was observed that the solenoid field was more effective than the C-shaped magnets, which supported the size measurement.
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